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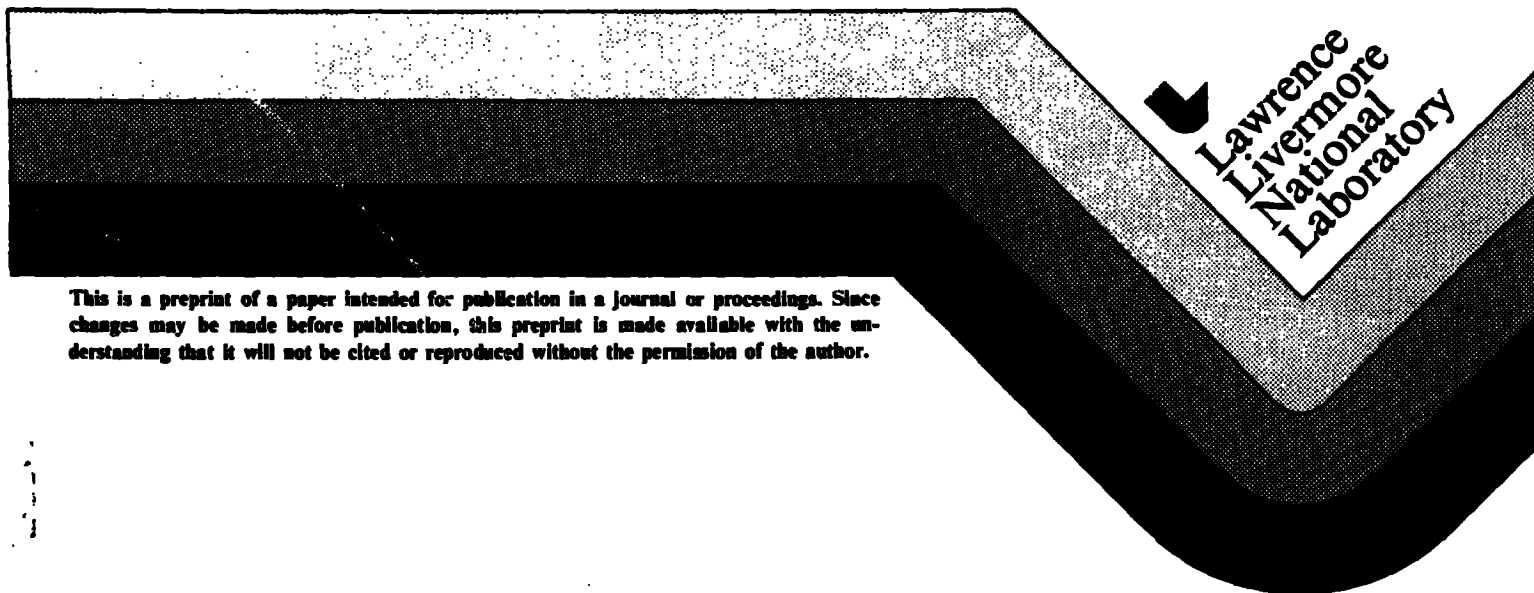
UCRL- 90716
PREPRINT

REQUIREMENTS OF QUANTITATIVE NDE IN
DEVELOPING FRACTURE CONTROL PLANS

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This paper was prepared for submittal to
Review of Progress in Quantitative NDE meeting
La Jolla, CA, July 8-13, 1984

November 1, 1984



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REQUIREMENTS OF QUANTITATIVE NDE IN DEVELOPING FRACTURE CONTROL PLANS

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INTRODUCTION

The goal of quantitative nondestructive evaluation, QNDE, is to quantify the results of an inspection: e.g., flaw size, porosity, inclusions, etc., such that results can be used in an engineering design evaluation. In this respect, it is important for the NDE community to closely interface with the design and materials engineers to establish the important quantifiable factors which can be readily used. One specific interaction is that of the fracture mechanics analysis and QNDE flaw size characterization. In this paper, we address the needs of the flaw size characterization in fracture control planning. Three factors; i.e., flaw size, flaw shape, and the probability of detection are discussed relative to linear-elastic fracture mechanics (LEFM).

This paper is divided into three sections; basics of LEFM, concepts of fracture control planning, and the requirements for flaw characterization. Special topics in fracture mechanics, such as elastic-plastic fracture or fracture of brittle materials (e.g., Weibull statistics) are not dealt with specifically, however, the same variables -- flaw size, shape and probability of detection are equally important under these constraints as with LEFM.

LINEAR-ELASTIC FRACTURE MECHANICS

Fracture mechanics is a design tool in which the fracture behavior of a structure can be predicted based on the components loading, geometry, and crack size. Linear-elastic fracture mechanics (LEFM) is a sub-set of the field of fracture mechanics. In LEFM, fracture is predicated on the magnitude of the elastic stress field in the vicinity of crack (the stress intensity factor, K_I) and the material's plane strain fracture toughness K_{Ic} . By ensuring that the design stress intensity is less than the material fracture toughness

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7045-ENG-48.

at the design conditions, unstable crack propagation can be avoided. This design relationship is analogous to the association of a components stress state and the materials tensile properties. LEFM thus enables the engineer to combine three factors; a materials resistance to crack propagation, component stress analysis, and inspection capabilities to provide a basis by which given materials and structures may be certified for fracture critical applications.

The stress intensity factor is related to the applied loading, geometry and flaw size by

$$K_I = C \sigma \sqrt{\pi a}$$

where, σ relates to loading,

C relates to component and flaw geometry,

and, a is the flaw size

Solutions for the stress intensity factors for many geometries can be easily found in available handbooks^{1,2} and technical publications. However, as will be discussed below, a few "basic" flaw geometries can be used for a majority of fracture applications. Failure will occur when the stress level (loading) and/or crack length is increased such that

$$K_I \geq K_{Ic}$$

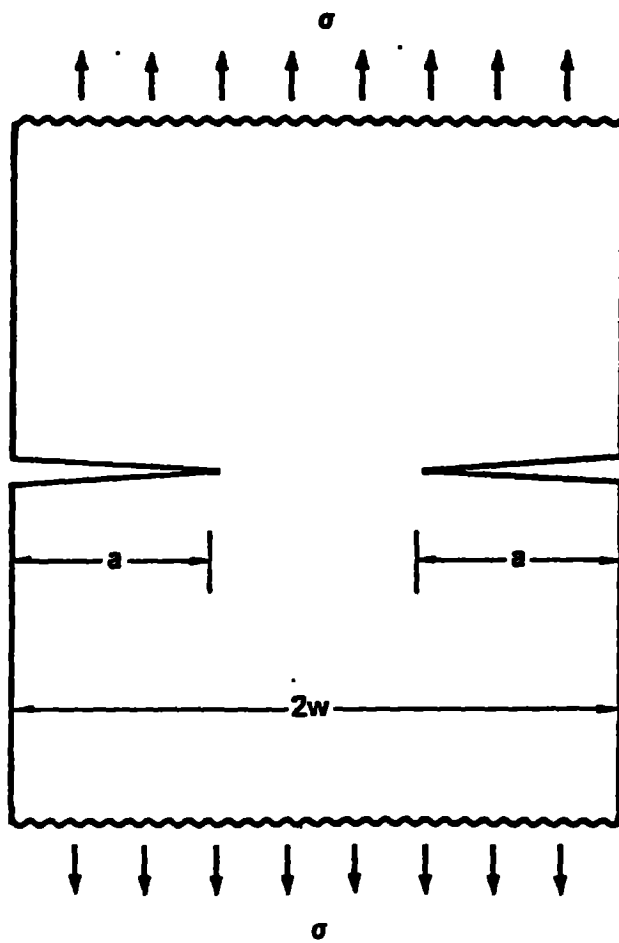
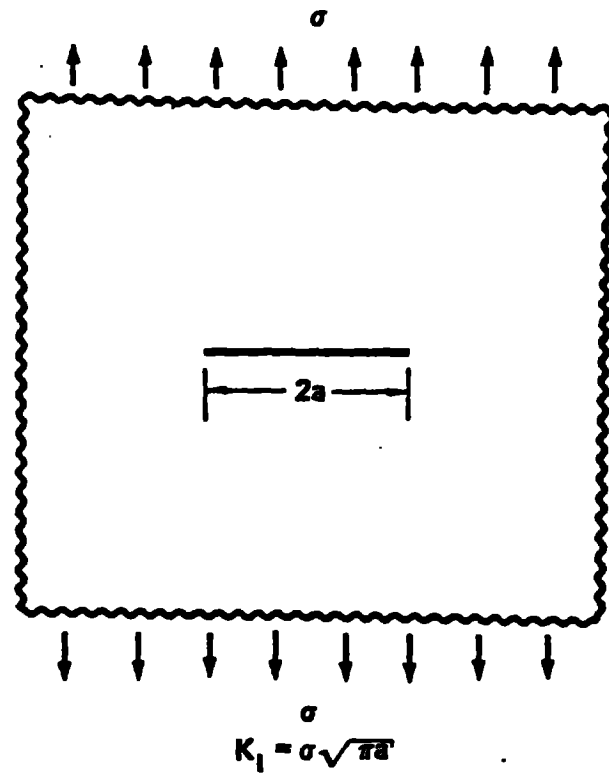
where K_{Ic} is the fracture toughness for a particular material (including any heat-treatment, weldments, etc.) at a given temperature and loading rate. The three factors which influence fracture control are: 1) allowable design stress level, 2) flaw size and shape which can be monitored by quantitative inspection techniques, and 3) choice of material.

Many of the cracks found in practice arise from such things as weld defects, arc burns, corrosion pits, fatigue or other defects introduced in the manufacturing process. These cracks are generally approximated by one of four basic flaw geometries: 1) through wall flaw (a double edge crack), 2) edge cracks, 3) embedded elliptical cracks and 4) semi-elliptical or thumbnail surface crack. Figures 1-3 show these geometries with the corresponding stress intensity solutions. While the solutions shown are specifically for flat plates, some solutions are also available for simple curved geometries; cylinders (e.g., pipes and pressure vessels) and spheres. Even when flaws do not "conveniently" fall into one of these four categories, the engineer will often make certain simplifying assumptions in order to use these well characterized geometries. QNDE aimed specifically at these geometries would be of immediate value to the design engineer.

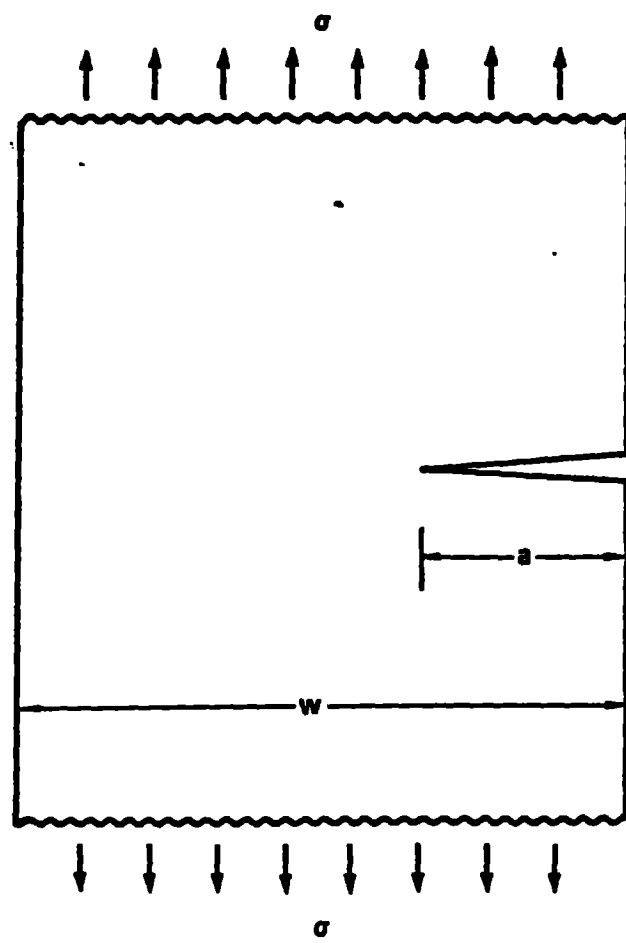
CONCEPTS OF FRACTURE CONTROL PLANNING

A fracture control plan is a specific set of analysis and recommendations developed for a particular structure to ensure its fracture integrity. It integrates three critical aspects of design; analysis, material testing, and component inspection and inspectability. The integration of these three factors define the operating load level or life of a component.

FIG. 1. Through-wall crack geometry in a large plate and associated stress intensity solution.



$$f\left(\frac{a}{w}\right) \rightarrow 1 \text{ for } w \gg a$$



$$f\left(\frac{a}{w}\right) \rightarrow 1 \text{ for } w \gg a$$

FIG. 2. Edge-notched geometries and associated stress intensity solutions.

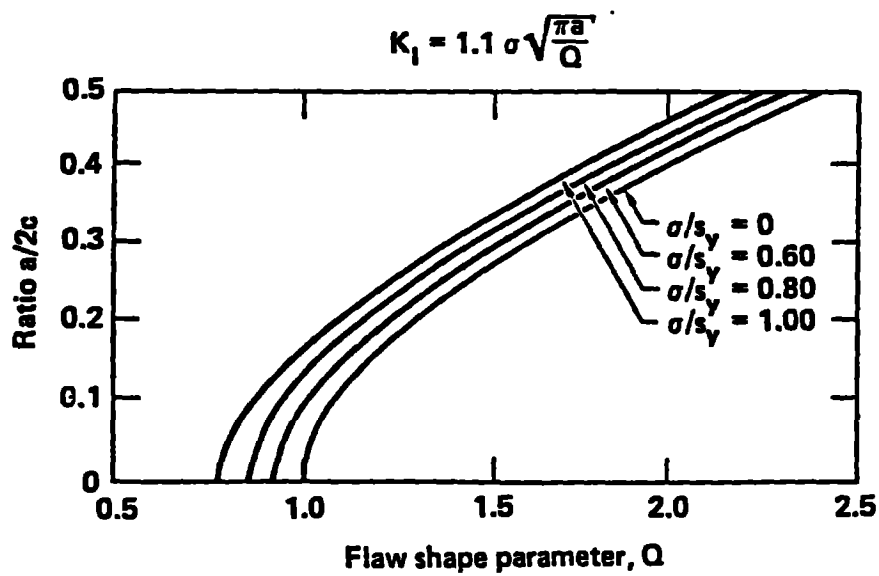
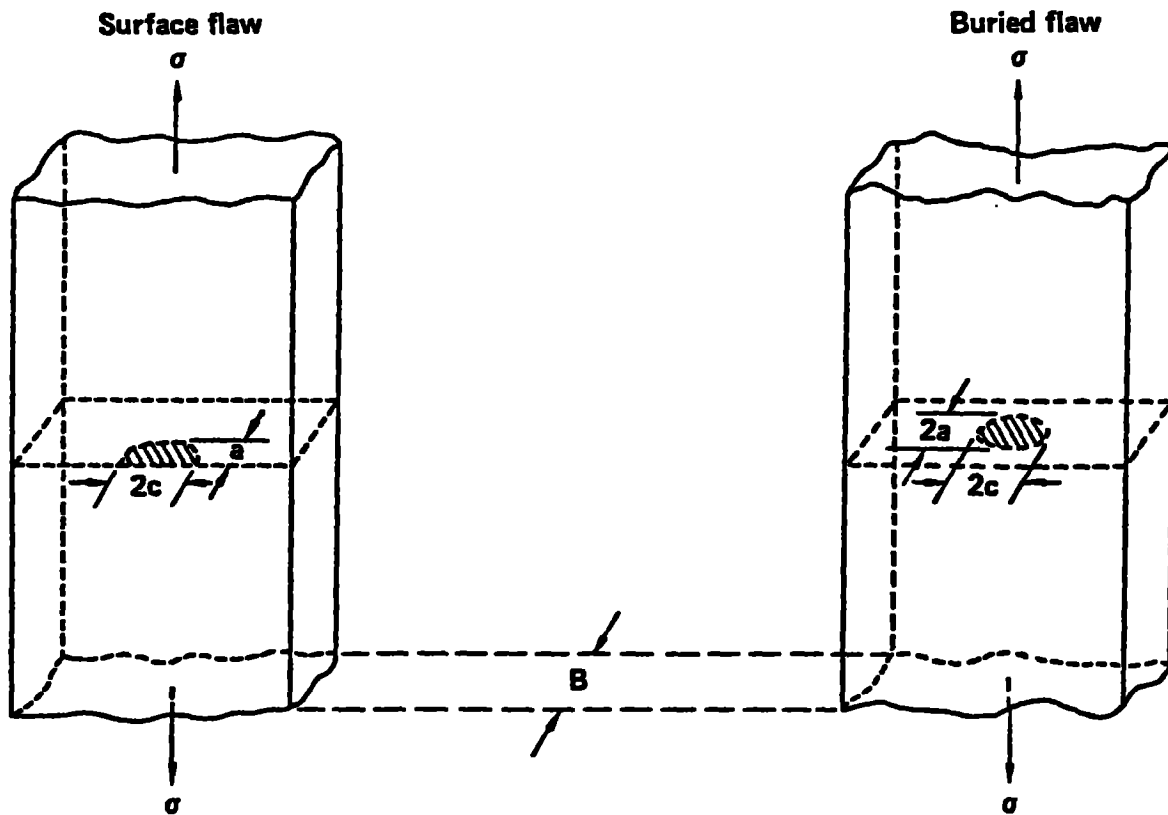


FIG. 3. Buried elliptical and thumb nail cracks and associated stress intensity solutions.

The goal of a fracture control plan is to establish "quantifiable" design guidelines. Four basic elements should be included in the fracture plan:³

1. Identification of the factor which may contribute to the fracture integrity of a structural member. This would include service conditions (e.g., temperature and environment), loading (including static, dynamic, and cyclic events), geometric or weld particulars, and required material and fabrication specifications.
2. Evaluate the relative importance of each of the factors identified; in particular, stress, toughness, flaw size limitations and detectability. Assess the contribution of fatigue crack growth and corrosion leading to the critical flaw size and evaluate the influence of residual stresses to the design stress calculations.
3. Determine trade-offs and compromises relative to the various design alternatives. By considering the influence of tensile stress, flaw size and material toughness with respect to cost, design life, load rating, inspectability, and inspection requirements an optimum design can be chosen. Include analysis of the factor of safety and fatigue life considerations. For example, if the initial flaw size, shape, and distribution can be accurately defined, then the factor of safety can be reduced (relative to the case of an ill-defined flaw population) without reducing overall component safety.
4. Recommendations of the specific design considerations to ensure the safety and reliability of the structure against failure. Such recommendations can include rated capacity of design stress level, material and/or fabrication qualification, allowable environments.

Depending upon the requirements and objective of the design, various concepts can be employed to establish critical flaw size requirements. Among these are: leak-before-break, through-thickness-yieldings, initial detectable flaw, and fatigue life rating (crack growth to a critical size). In general, the better defined the crack size and shape, the more precise and quantitative the fracture control plan can be.

REQUIREMENTS OF FLAW SIZE CHARACTERIZATION

A number of elements are critical to quantitative flaw characterization for a fracture evaluation. The critical elements are flaw size, shape, orientation, and probability of detection. Flaws defined in most fracture evaluations are 2-dimensional; i.e., they are planar flaws with an ideally sharp crack front. This is in contrast to the flaws often evaluated using QNDE techniques (e.g., Born inversion) in which the flaws are defined as an arbitrary ellipsoid. Further, to be compatible with the fracture mechanics design analysis, the crack front must be well defined and the crack shape should be classified according to one specific known stress intensity solutions shown in Figs. 1-3.

The critical flaw size for a given structure is a function of the fracture toughness of the material, geometry of the component and applied loading. The plane strain fracture toughness of different materials varies dramatically as shown in Table 1. Even within specific classes of materials there can be a large range of toughnesses resulting from different processing, heat-treatment, chemistry, etc. Thus, depending upon the loading and geometry, the critical flaw size which can lead to unstable crack propagation can range from a few mils (.001 in.) to many feet. QNDE must be capable of "adapting" to the needs of the design in reliably finding and accurately describing flaws in this range.

For cases in which a "system" is under evaluation, a nuclear reactor piping system for example, a probabilistic fracture mechanics approach can be employed. Figure 4 shows a typical methodology for a probabilistic fracture mechanics analysis.⁴ In a probabilistic analysis, the loading, flaw size distribution, inspection capability and material properties are treated as random variables. Unfortunately, the flaw size distribution is probably the least well defined and has the largest effect on the probabilistic failure result. Description of the flaw size distribution actually requires a number of different inputs; probability of flaw existence, the flaw shape, aspect ratio and orientation, the flaw location, and the flaw size. However, data on these parameters are not readily available, and what is available is limited to specific cases.

In addition to the flaw size distribution, the probability of detection is another critical element which must be defined for the fracture analysis.⁴ A number of distributions have been proposed as shown in Fig. 5.⁴ However, the amount of supporting data is very limited and, what little data there is, is very much a function of the conditions of the inspection. Further, laboratory tests designed to establish the probability of detection are often skewed since the NDE inspector "knows" that some crack must exist. Laboratory conditions are often dramatically different than the conditions under which the actual parts must be inspected. Even with these "warnings," Fig. 5 shows that cracks greater than 0.5 inch can often be missed in an ultrasonic inspection under in-service conditions.

Table 1. The Fracture Toughness, K_{Ic} , of common structural materials ranges from a few $\text{ksi} \sqrt{\text{in}}$ to 300+ $\text{ksi} \sqrt{\text{in}}$

Glass	.1 - .3 $\text{ksi} \sqrt{\text{in}}$
Beryllium	5 - 8 $\text{ksi} \sqrt{\text{in}}$
Aluminum	18 - 33 $\text{ksi} \sqrt{\text{in}}$
Ferretic Steels	40 - 140 $\text{ksi} \sqrt{\text{in}}$
Stainless Steels	150 - 350 $\text{ksi} \sqrt{\text{in}}$

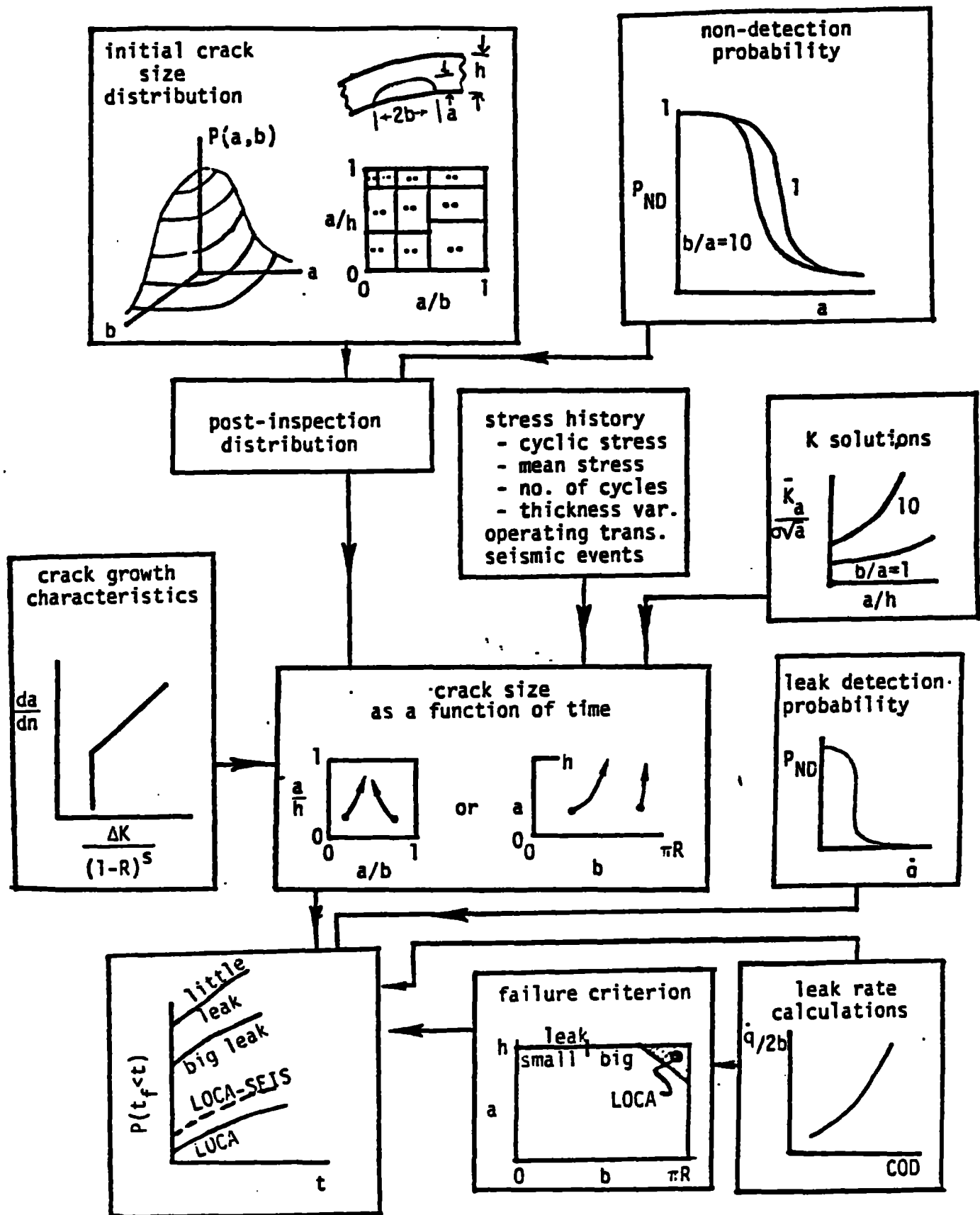


FIG. 4. Schematic Diagram of Steps in Analysis of Reliability of a Given Weld Location.⁴

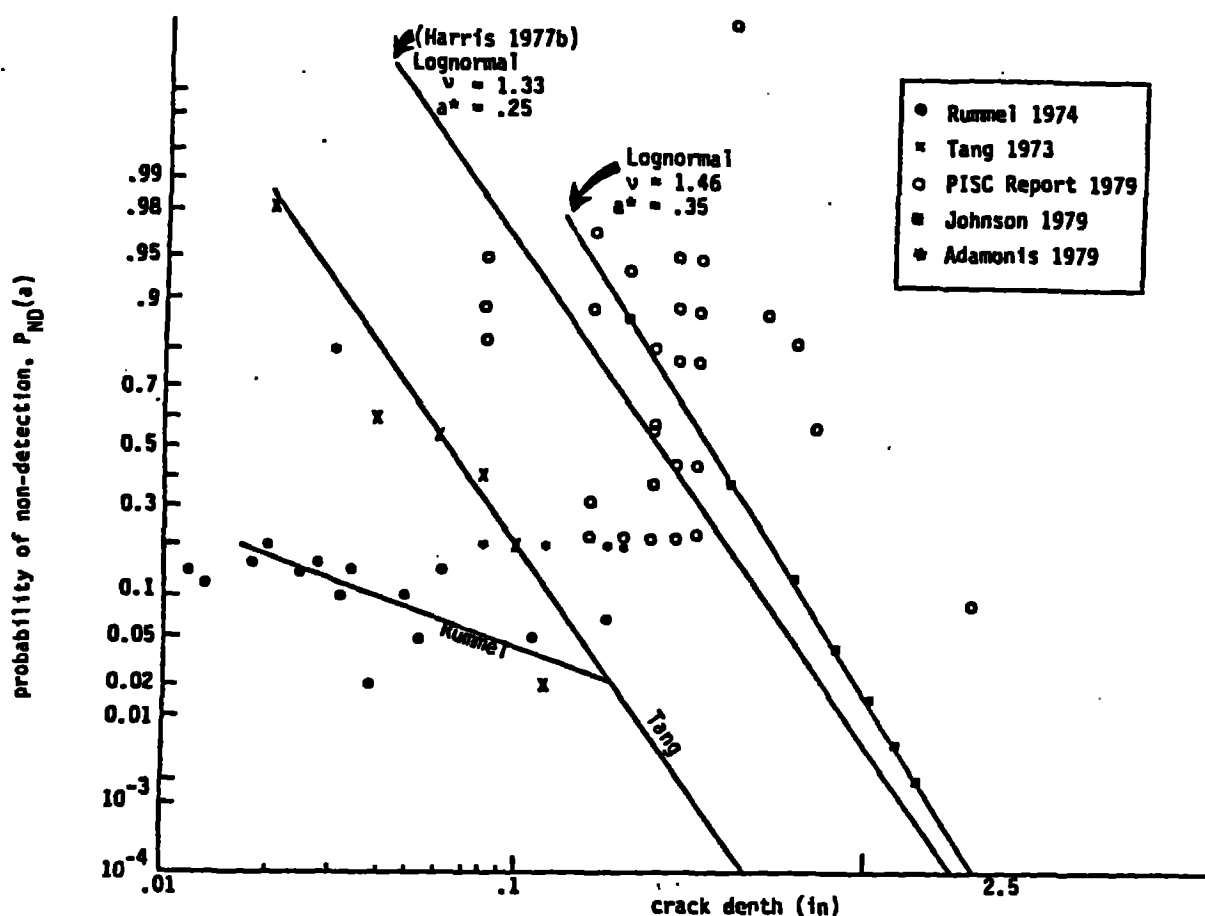


FIG. 5. Probability of Non-Detection of a Crack as a Function of its Depth for an Ultrasonic Inspection. ⁴

SUMMARY

The requirements of QNDE to a fracture mechanics analysis lies in the ability to accurately define the flaw size, shape, and distribution. Since a linear-elastic fracture mechanics analysis requires knowledge of the stress intensity factor associated with a given flaw, certain flaw geometries (with known stress intensity solutions) can be more readily used. A number of common flaw geometries were presented. While many other geometries are sometimes used, Fig. 1-3 cover a majority of the fracture mechanics design applications. Further, to develop the confidence in flaw sizes and shapes predicted by NDE for a quantitative evaluation, increased emphasis must be placed on developing reliable statistics for the probability of flaw detection and the size and shape distribution for different materials and processing histories.

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